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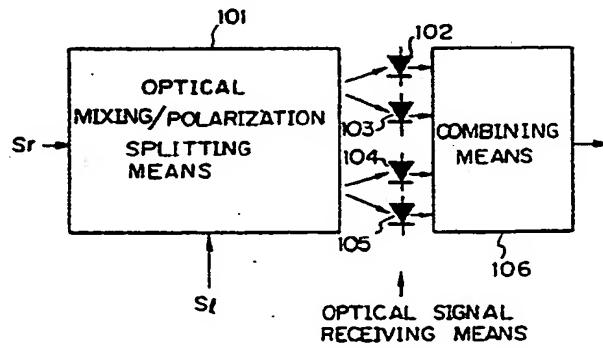
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(54) Dual balanced optical signal receiver.

(57) An optical signal receiver comprising an optical mixing/polarization splitting unit (101) for producing IF optical signals having two orthogonally polarized components, an optical signal receiving unit (102-105) for producing four corresponding IF electric signals, and a combining circuit (106) for combining two IF electric signals having one polarization with the other two IF electric signals having the other polarization, suppressing fluctuation of the polarization and the intensity noise of the related local optical signal. The intensity noise suppression is also effective for IF electric signals having a higher frequency range.

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Fig. 7



DUAL BALANCED OPTICAL SIGNAL RECEIVER**I. Field of the Invention**

The present invention relates to a dual balanced optical signal receiver for use in a practical coherent lightwave communication system.

**2. Description of the Related Art**

In a lightwave communication system, a direct detection method is usually employed in which a received optical signal transmitted via an optical transmission line is directly supplied to an optical receiving element and then transformed thereby into an electric signal. In a coherent lightwave communication system, a so-called homodyne detection method or a heterodyne detection method is known, in which a very pure laser device is used as a local oscillation optical source and the local oscillation optical signal is mixed with the received optical signal. This method has a superior receiver sensitivity to that of the aforesaid direct detection method. Accordingly, in the coherent lightwave communication system, it is possible to enlarge the repeater spacing, and thus reduce the number of repeaters. Further, where the coherent lightwave communication system is introduced in a subscriber network, it is possible to increase the number of branches, and thus realize an economical arrangement of the optical transmission lines.

Recently, in such homodyne detection or heterodyne detection techniques, there has arisen a demand for a suppression of a reduction in interference efficiency due to a fluctuation of a polarization plane between the received optical signal and the local oscillation optical signal, and a reduction in receiver sensitivity due to an intensity noise of the local oscillation optical signal (hereinafter referred to as intensity noise).

To cope with the above demand, various techniques have been proposed in the prior art, as will be explained in detail hereinafter. The problems occurring in the prior art optical signal receiver are, first it is difficult to increase receiver sensitivity since a part of both the received optical signal and the local oscillation optical signal is left unused, and second, it is difficult to maintain a suppression of intensity noise contained in a local oscillation optical signal regardless of a fluctuation of the polarization.

An object of the present invention is to provide a dual balanced optical signal receiver which can realize a highly stable reception of a coherent lightwave signal.

A further object of the present invention is to provide a dual balanced optical signal receiver which can realize a highly stable reception of a coherent lightwave signal regardless of variances in operation characteristics between a pair of optical signal receiving means.

The above objects are attained by combining a balanced mixer balanced optical signal receiver and a polarization-diversity optical signal receiver.

The present invention will be more apparent from the ensuing description with reference to the accompanying drawings, wherein:

Fig. 1 is a schematic block diagram of a conventional coherent lightwave communication system;

Fig. 2 is a schematic block diagram of a prior art optical system;

Fig. 3 is a graph exhibiting C/N characteristic curves in terms of the intensity noise of the local oscillation signal;

Fig. 4 is a schematic block diagram of a known balanced-mixer receiver;

Fig. 5 is a view of a balanced-mixer receiver of Fig. 4;

Fig. 6 is another view of a balanced-mixer receiver of Fig. 4;

Fig. 7 illustrates a principle construction of a dual balanced optical signal receiver according to the present invention;

Fig. 8 is a schematic block diagram of a dual balanced optical signal receiver according to a first embodiment of the present invention;

Fig. 9 illustrates a dual balanced optical signal receiver according to a second embodiment of the present invention;

Fig. 10 is a view of the polarization splitting part used in Fig. 9;

Fig. 11 is a schematic block diagram of a dual balanced optical signal receiver according to a third embodiment of the present invention;

Fig. 12 illustrates a dual balanced optical signal receiver according to a fourth embodiment of the present invention;

Fig. 13 is a circuit diagram of a combining circuit according to a first example of the present invention;

Fig. 14 is a circuit diagram of a combining circuit according to a second example of the present invention;

Fig. 15 is a block diagram of a combining circuit according to a third example of the present invention;

Fig. 16 is a graph of intensity noise suppression characteristics;

Fig. 17 is a principal block diagram of an intensity noise suppression arrangement;

Fig. 18 is a schematic block diagram of a first type of intensity noise suppressor;

Fig. 19 is a schematic block diagram of a second type of intensity noise suppressor;

Fig. 20 is a schematic block diagram of a third type of intensity noise suppressor;

Fig. 21 is a schematic block diagram of a fourth type of intensity noise suppressor; and

Fig. 22 is a schematic block diagram of a dual-balanced optical signal receiver provided with an intensity noise suppressor.

Before describing the preferred embodiments, a prior art optical signal receiver will be explained for reference.

Figure 1 is a schematic block diagram of a conventional coherent lightwave communication system. The system of the figure is operated under a homodyne detection method or a heterodyne detection method. In this system, an optical signal is transmitted, via a single mode fiber 12, from an optical signal transmitter to an optical signal receiver 10. In the receiver 10, both the received optical signal and a local oscillation optical signal from a local oscillation laser 14 are mixed at a photomixer 13. The thus mixed optical signal is projected onto an optical signal receiving means 15, such as a photodiode, and then transformed into a corresponding electric signal to be applied to an amplifier 16. The output signal from the amplifier 16 is an intermediate frequency (IF) signal of, for example, several GHz.

In the above coherent lightwave communication system, the transmitted optical signal from the transmitter 11 is obtained by previously modulating, directly or indirectly, a laser to a linear polarization lightwave. When the linear polarization lightwave travels along a long distance optical transmission line composed of an ordinary single mode fiber 12, the lightwave changes to an elliptical polarization lightwave or the polarization plane of the lightwave is rotated. This is called a fluctuation of polarization. When the fluctuation is large, an interference efficiency at the photomixer 13 between the local oscillation optical signal and the received optical signal is deteriorated, and in the worst case a normal reception of the transmitted optical signal can not be realized.

To overcome the above mentioned problem of reduced interference efficiency, a polarization-diversity reception method was disclosed in, for example, "FOURTH INTERNATIONAL CONFERENCE ON INTEGRATED OPTICS AND OPTICAL FIBER COMMUNICATION, Main Conference Technical Digest, June 27-30, 1983, Tokyo Japan, Fig. 1. Figure 2 is schematic block diagram of a prior art optical receiver operated under such a polarization-

diversity reception method. In Fig. 2, a received optical signal  $S_r$ , sent via an optical transmission line (12 in Fig. 1), is split into two orthogonally polarized components by a polarization splitting element 21 and the thus split polarization components are commonly mixed, at a photomixer 23 and a photomixer 26, respectively, with the local oscillation optical signal produced by a local oscillation laser 24. In this case, the two orthogonally polarized component for mixing with the received optical signal  $S_r$  are created by the same local oscillation optical signal  $S_L$ . To this end, a halfwave plate 25 is located between the photomixers 23 and 26. As is known, the halfwave plate is used for changing an S polarization lightwave onto a P polarization lightwave, and vice versa. Also, a reflecting plate 22 is located to project one of the polarization lightwaves to the corresponding photomixer 26.

The optical signals output from the photomixers 23 and 26 are projected onto optical signal receiving elements 27 and 28, respectively and transformed into corresponding electric signals. These electric signals are then fed to a combining means. That is, in the combining means, the electric signals are amplified by amplifiers 29 and 30, and then the thus amplified output signal from the amplifier 29 and the thus amplified output signal via a phase shifter for a phase adjustment from the amplifier 30, are combined by a combining circuit 32. The phase shifter 31 is controlled to produce a maximum combined output signal.

Thus, in the polarization-diversity receiver of Fig. 2, the electric signals can be obtained from at least either the optical signal receiving element 27 or the element 28, even when the fluctuation of the polarization is relatively large, and thus a normal reception of the transmitted optical signal can be guaranteed, to a certain extent.

In the construction of the coherent lightwave receiver, a factor other than the above-mentioned interference efficiency is also very important and must be taken into consideration. This factor is a so-called intensity noise contained in the local oscillation optical signal  $S_L$ . Figure 3 is a graph showing C/N characteristic curves in terms of the noise intensity of the local oscillation signal. The ordinate indicates a carrier-to-noise (C/N) ratio in dB, and the abscissa indicates an intensity of a lightwave of the local oscillation optical signal  $S_L$ . In the receiver of Fig. 1 or 2, the stronger the intensity of a lightwave from the local oscillation, laser 14 or 24, the greater the improvement in the C/N ratio, i.e., a minimum detectable power. It can be seen from the abscissa of the graph that a C/N value becomes better. It is, however, important to note that, even if the intensity of the lightwave is further strengthened, the C/N value cannot reach a

shot noise level, which is an ideal level, in a case where the intensity noise is relatively high due to, for example, an instability of the local oscillation laser 14 or 24. As a result, the C/N characteristic is deteriorated (i.e., a reincrease of the curve seen at right side of the Figure). In such circumstances, a local oscillation lightwave having a low intensity noise must be used to improve the C/N characteristic, or the intensity noise per se must be suppressed.

To implement the above, a balanced mixing method has been proposed in, for example, "OPTICS LETTERS, Vol. 8, No. 8, August 1983, pages 419-421, in an article entitled, "Local-oscillator excess-noise suppression for homodyne and heterodyne detection".

Figure 4 is a schematic block diagram of a known balanced-mixer receiver. In Fig. 4, a received optical  $S_r$  is mixed at a photomixer 42 with a local oscillation optical signal  $S_L$  produced from a local oscillation laser 44. A photomixer 42 can divide the optical power from a local oscillation laser 44 by two, and output two optical signals having the same power. Accordingly, two optical signals are output from the photomixer 42 and projected onto optical signal receiving elements 43 and 45, to be transformed into corresponding electric signals. These electric signals are then applied, via respective amplifiers 46 and 47, to a subtractor 48. The optical signals output from the photomixer 42, i.e., beat signal components between the optical signals  $S_r$  and  $S_L$ , are shifted in phase by 180°, while the intensity noise components contained in the two beat signals remain in phase with each other. Therefore, when the two beat signals from the amplifiers 46 and 47 are subtracted from each other, the beat signal components per se are added to each other, but the intensity noise components per se are cancelled. Thereby, the intensity noise of the local oscillation optical signal  $S_L$  can be largely suppressed.

Figure 5 is a view of a balanced-mixer receiver of Fig. 4. A received optical signal  $S_r$  and a local oscillation optical signal  $S_L$  are simultaneously applied to a photomixer 42 and the thus mixed optical signals are then projected onto respective optical signal receiving elements 52 and 53 connected in series, and an electric signal appearing at an intermediate connecting point PNT is applied to an amplifier 54. The series connection of the optical signal receiving elements 52 and 55 operates in an identical manner to the subtractor 48 of Fig. 4, and therefore, the beat signal components are added while the intensity noise components are cancelled.

Figure 6 is another view of a balanced-mixer receiver of Fig. 4. In Fig. 6, a 3 dB photocoupler is used as the aforesaid photomixer to which both the optical signals  $S_r$  and  $S_L$  are applied. The thus

mixed output optical signals are projected onto the optical signal receiving elements 56, 57 and the related electric signal appearing at the intermediate connecting point PNT is amplified by an amplifier 58, so that an addition of the two beat signal components and a cancellation of the intensity noise components can be realized, as shown in Fig. 5.

Returning to Figs. 1 and 2, a problem arises in that a part of the mixed optical signal are left unused, and this causes a loss of the beat signal. For example, in Fig. 1, the mixed optical output signal radiated from the top of the photomixer 13 is discarded. Similarly, in Fig. 2, the mixed optical output signal radiated from the top of the photomixer 23 is discarded. Further, the C/N (carrier to noise) of each optical signal receiver of Figs. 1 and 2 is deteriorated due to the intensity noise of the local oscillation optical signal. Accordingly, in the prior art, it is difficult to increase the sensitivity of a receiver, as mentioned previously. Further, returning to Fig. 4, the prior art optical signal receiver can suppress the intensity noise, but the interference efficiency varies in accordance with the fluctuation of the polarization, whereby the receiver sensitivity is also varied, and in the worst case, i.e., when the polarization angle of one of the signals  $S_r$  and  $S_L$  becomes perpendicular to that of the other signal, it is impossible to maintain a normal reception of the transmitted optical signal. To cope with the above problems, the optical signal receiver of the present invention is created by combining both the polarization diversity technique and the balanced mixing technique.

Figure 7 illustrates a principle construction of a dual balanced optical signal receiver according to the present invention. The construction of the dual balanced optical signal receiver comprises mainly an optical mixing/polarization splitting means 101, optical receiving means 102 through 105, and a combining means 106. The means 101 produces optical signals having an intermediate frequency (IF) by mixing a received optical signal  $S_r$  with a local oscillation optical signal  $S_L$ , and then splits the thus mixed signal into two orthogonally polarized components. Alternatively, the means 101 produces optical signals by splitting the received optical signal into two orthogonally polarized components and then mixing each of the thus split orthogonally polarized components with the local oscillation signal  $S_L$ . Thus, the optical mixing/polarization splitting means 101 produces four polarized components. The four polarized components are applied to respective optical signal receiving elements 102 through 105, i.e., the optical signal receiving means, so that the polarized components are transformed into corresponding electric signals having an intermediate frequency (IF). The

IF electric signals are received by the combining means I06 and the two signals having the same polarization (S) are combined, and the other two signals having the other polarization (P) are also combined.

The dual balanced optical signal receiver operates in such a manner that a differential signal is obtained between two IF electric signals each having the intensity noise components (contained in a local oscillation optical signal) which are in phase, i.e., an undesirable intensity noise. Further, the related differential signals are combined in phase to realize the polarization diversity reception, and thereby the undesirable effect due to the fluctuation of the polarization can be suppressed.

Figure 8 is a schematic block diagram of a dual balanced optical signal receiver according to a first embodiment of the present invention. In Fig. 8, the aforesaid optical mixing/polarization splitting means I01 (Fig. 7) is comprised of a photomixer I13 and polarizing prisms I15, I16. The optical signal receiving elements I17 and I20 correspond to the aforesaid optical signal receiving means I02 through I05 (Fig. 7). The aforesaid combining means I06 (Fig. 7) is comprised of amplifiers I21, I22 and a combining circuit I23.

The received optical signal  $S_r$ , given, via an optical transmission line I12, from an optical signal transmitter I11, is applied first to a mixing part, i.e., the photomixer I13, and mixed therein with a local oscillation optical signal  $S_L$  from a local oscillation laser I14, so that two mixed optical signals  $S_{x1}$ ,  $S_{x2}$  are obtained, which are then projected onto respective polarizing prisms I15, I16 which form a polarization splitting part.

The optical signal receiving elements I17 and I20 are connected in series, as are the elements I18 and I19, as is shown in Fig. 5 or 6. The intermediate connecting points PNT1 and PNT2 therebetween, are led to respective amplifiers I21 and I22. Here, a subtracting means is formed by pairs of series connected elements I17, I20 and I18, I19 and the intermediate connecting points PNT1 and PNT2, followed by the combining means. The polarization splitting part, i.e., the polarizing prisms I15, I16, separate the mixed optical signals  $S_{x1}$ ,  $S_{x2}$  into two orthogonally polarized components to obtain, a total of four mixed and split optical signals  $S_{y11}$ ,  $S_{y12}$ ,  $S_{y21}$ , and  $S_{y22}$ . The signals  $S_{y11}$  and  $S_{y21}$ , for example, S polarized wave signals, are projected onto the optical signal receiving elements I17 and I20, respectively, while the signals  $S_{y12}$  and  $S_{y22}$ , for example, the P polarized wave signals, are projected onto the elements I18 and I19, respectively. In this case, the intensity noise components from the laser I14, contained in the signals  $S_{y11}$  and  $S_{y21}$ , are in phase with each other and also the intensity noise components from the laser I14 con-

tained in the signals  $S_{y12}$  and  $S_{y22}$  are in phase with each other. Accordingly, the S side intensity noise components are cancelled at point PNT1 by the series connected elements I17 and I20. Similarly, the P side intensity noise components are cancelled at point PNT2 by the series connected elements I18 and I19. Conversely, the beat signal components contained in the S side signals  $S_{y11}$  and  $S_{y21}$  are added together at point PNT1 and amplified by the amplifier I21. Similarly, the beat signal components contained in the P side signals  $S_{y12}$  and  $S_{y22}$  are added together at the point PNT2 and amplified by the amplifier I22. Note, it is not certain whether the signals  $S_{y11}$  and  $S_{y21}$  indicate the S polarized wave signals, as explained above, or the P polarized wave signals. This also holds true for the signals  $S_{y12}$  and  $S_{y22}$ , as these two signals are complementary to the above two signals  $S_{y11}$  and  $S_{y21}$ . The amplified signals from the amplifiers I21 and I22 are supplied to the combining circuit I23, in which the amplified signals are adjusted in phase relative to each other and then added together. The relative phase adjustment can be achieved by using, for example, the phase shifter 31 shown in Fig. 2, so that the added signal is maximized. Thus, a stable reception of the transmitted optical signal can be realized, since the P polarized wave signal and S polarized wave signal can be fully combined without any loss, even if there is a fluctuation of the polarization in the transmitted optical signal.

Figure 9 illustrates a dual balanced optical signal receiver according to a second embodiment of the present invention. In Fig. 9, the optical mixing/polarization splitting means I01 (Fig. 7) is comprised of a 3 dB photocoupler I33 as the mixing part and a polarization beam splitter I35 as the polarization splitting part. The optical signal receiving elements I36 through I39 correspond to the optical signal receiving means I02 through I05 (Fig. 7).

An optical transmission line I32 can be made of a single mode fiber as usual. However, other fibers I26 through I29, located in the vicinity of the input/output ports provided with the 3 dB photocoupler I33, are preferably made of polarization-maintaining fibers. Using a polarization maintaining fiber, the local oscillation optical signal  $S_L$  from a local oscillation laser I34 is projected, via the input fiber I27, onto the first input port of the photocoupler I33 with a polarization plane rotated by 45° relative to the longitudinal axis of the fiber I27. This enables the same intensity of the local oscillation laser to be supplied for both the P polarized wave and the S polarized wave in the received optical signal  $S_r$ . On the other hand, although the transmitted optical signal from an optical signal transmitter I31 is given, through the line

I32, with a random polarization direction, the received optical signal  $S_r$  is supplied to the second input of the photocoupler I33 by way of the input fiber I26. Accordingly, a photomixing operation is performed in the photocoupler I33 and the thus mixed optical signals are then applied, via the polarization-maintaining fibers I28 and I29, to the polarization beam splitter I35, which is made of, for example, a crystal exhibiting a complex index of refraction, such as a calcite, to produce therefrom the split S and P polarized wave signals. As a result, the beam splitter I35 produces four mixed and split optical signals  $S_{y11}$ ,  $S_{y12}$ ,  $S_{y21}$ , and  $S_{y22}$ , as in Fig. 8. For example, the P polarized wave mixed and split optical signals  $S_{y12}$  and  $S_{y22}$  are sent to the optical signal receiving elements I37 and I39, while the S polarized wave mixed and split optical signals  $S_{y11}$  and  $S_{y21}$  are sent to the elements I36 and I38.

The optical signal receiving elements I36 and I38 are connected in series, as are the elements I37 and I39, and the IF electric signals appearing at the respective intermediate connecting points are processed in the combining means I06, as in Fig. 8. In the combining means I06, the IF output electric signal from the elements 36 and 38 and the IF output electric signal from the elements 37 and 39 are adjusted in phase to produce a maximized IF electric signal. In this case, the relative phase difference between the two IF output electric signals is caused by the difference in length of the fibers or jitter occurring in the fibers.

Figure 10 is a view of the polarization splitting part used in Fig. 9. The mixed optical output from a polarization-maintaining fiber I41 (corresponding to I28 or I29 in Fig. 9) is applied, via a suitable lens I42, to a polarization beam splitter I43 (corresponding to I35 in Fig. 9) and separated therein into both an S polarized wave signal and a P polarized wave signal. The S and P polarized wave signals are converged by respective lenses I44 and I45, and finally, sent to optical signal receiving elements I46 and I47 (corresponding to I36, I37 or I38, I39 in Fig. 10). In the above polarization splitting system, the lenses I44 and I45 may be omitted if a suitable focal length of the lens I42 is used.

The differences between the first embodiment (Fig. 8) and the second embodiment (Fig. 9) of the present invention are as follows. In the first embodiment, the optical system is relatively larger in size than the second embodiment, since two polarizing prisms I15 and I16 are employed in the first embodiment. Conversely, in the second embodiment, two mixed optical signals are split into two S polarized wave and two P polarized wave mixed and split optical signals  $S_{y11}$ ,  $S_{y21}$ ,  $S_{y12}$  and  $S_{y22}$ , by a single polarization splitting part, i.e., the split-

ter I35. This enables a reduction in size of the related optical system. In addition, the second embodiment is more advantageous than the first embodiment from the viewpoint of an easy matching of the polarization planes in the mixing part, i.e., the 3 dB photocoupler, due to the use of the polarization-maintaining fibers I26 through I29.

Figure II is a schematic block diagram of a dual balanced optical signal receiver according to a third embodiment of the present invention. In Fig. II, reference numeral I54 denotes a local oscillation laser (corresponding to I14 in Fig. 8), I58 through I61 optical signal receiving elements (I17 through I20 in Fig. 8), I62 and I63 amplifiers (I21 and I22 in Fig. 8), and I64 a combining circuit (I23 in Fig. 8). External to the optical receiver are arranged an optical signal transmitter I51 (III in Fig. 8) and an optical transmission line I52 (II2 in Fig. 8).

The aforesaid optical mixing/polarization splitting means I01 (Fig. 7) is comprised of the polarization splitting part and the mixing part in this order. Note, in the first and second embodiments, the mixing/polarization splitting means is comprised of the mixing part and the polarization splitting part in this order, in the direction of the transfer of the signal.

The received optical signal  $S_r$ , given, via the line I52 and a lens I53, from the transmitter I51, is applied first to the polarization splitting part, at a polarization splitting element I55, to separate it into an S polarized wave received signal and a P polarized wave received signal. At the same time, the local oscillation optical signal  $S_L$  is applied first to the polarization splitting part, at a polarization splitting element I56, to separate it into an S polarized wave local signal and a P polarized wave local signal with the same intensity for each polarization. Then the above mentioned signals are mixed with each other in the mixing part, i.e., a photomixer I57, so that four split and mixed optical signals  $S_{y11}$ ,  $S_{y12}$ ,  $S_{y21}$ ,  $S_{y22}$  are produced and projected onto respective optical signal receiving elements I58 through I61. The elements I59 and I60 are supplied with optical signals having the same polarized component, such as P (or S), and the elements I58 and I61 are supplied with optical signals having the same polarized component, such as S (or P). In this case, the intensity noise of the local oscillation optical signal  $S_L$ , given to the optical signal receiving element I59, and the intensity noise given to the element I60 have the same phase, i.e., are in phase. Also, the intensity noise of the local oscillation optical signal  $S_L$ , given to the optical signal receiving element I58 and the intensity noise given to the element I61 have the same phase, i.e., are in phase. Accordingly, the intensity noise components are cancelled, on one hand, by the series connected elements I59 and I60, and on the other

hand, by the series connected elements 158 and 161. Conversely, one polarization side beat signal components are added by the series connected elements 158 and 161, and the other polarization side beat signal components are added by the series connected elements 159 and 160. The thus emphasized beat signal components are further amplified by respective amplifiers 162 and 163 and then adjusted to be in phase with each other to produce, when combined, a maximum IF output signal, from the combining circuit 164.

Figure 12 illustrates a dual balanced optical signal receiver according to a fourth embodiment of the present invention. In Fig. 12, the optical mixing/polarization splitting means 101 (Fig. 7) is comprised of a polarization beam splitter 173 as the polarization splitting part and 3 dB photocouplers 175 and 176 as the mixing part. The optical signal receiving elements 177 through 180 correspond to the optical signal receiving means 102 through 105 (Fig. 7).

An optical transmission line 179 can be made of a single mode fiber, as usual, and a local fiber 127 can be made of a polarization maintaining fiber. A transmitted optical signal from an optical signal transmitter 171 is applied, via an optical transmission line 172, to the polarization beam splitter 173, as an optical received signal  $S_r$ . At the same time, a local oscillation optical signal  $S_L$  is applied from a local oscillation laser 174 with a polarization plane rotated by 45° relative to the principal axis of the polarizing beam splitter. The local oscillation optical signal  $S_L$  is separated into two independent polarized wave signals separated (P, S) having the same intensity. To the polarization beam splitter 173. In the splitter 173, the signal  $S_r$  is separated into an S polarized wave signal and a P polarized wave signal, as is the signal  $S_L$ . These S and P polarized wave split signals are mixed in the 3 dB photocouplers 175 and 176 to produce four split and mixed optical signals  $S_{y11}$ ,  $S_{y12}$ ,  $S_{y21}$ , and  $S_{y22}$  which are then sent to the respective optical signal receiving elements 177 through 180. For example, the S polarized wave component signals are given to the elements 177 and 178, while the P polarized wave component signals are given to the elements 179 and 180. Since the elements 177 and 178 are connected in series, as are the elements 179 and 180, the intensity noise contained in the local signal  $S_L$  is cancelled, while effectively maintaining the polarization diversity, and finally, after adjustment of the phases, the combining means 106 produces the maximum IF output signal, as previously explained.

The difference between the third embodiment (Fig. 11) and the fourth embodiment (Fig. 12) resides in that, in the third embodiment, since the related optical system is set up with the use of spatial

optical beams, it is necessary to effect a very fine adjustment of the wave planes appearing in the system. Conversely, in the fourth embodiment, the wave plane matching is easily performed due to the employment of the optical waveguide mixers.

Figure 13 is a circuit diagram of a combining circuit according to a first example of the present invention. Each of the aforesaid combining circuits in the combining means 106 can be constructed with the circuit arrangement of Fig. 13. Referring to Fig. 13 and, for example, Fig. 8 (first embodiment), input terminals 181 and 182 are respectively connected to the amplifiers 121 and 122 and the output terminal 187 produces the IF output signal. A phase control means is employed in the combining circuit, which means is realized as a delay line 185 for a phase adjustment (similar to the phase shifter 31 in Fig. 2). Further the combining circuit employs therein a signal intensity control means which is realized as level weighting circuits 184 and 185. Furthermore, the combining circuit employs therein a summing means which is realized as a single stage amplifying transistor 186 having a common gate to the signal paths led to the input terminals 181 and 182.

Figure 14 is a circuit diagram of a combining circuit according to a second example of the present invention. This second example comprises a slight modification of the first example (Fig. 13). That is, the summing means is realized not by the aforesaid single stage amplifying transistor (refer to 186 in Fig. 13), but by a differential amplifying transistor pair 188. In this case, an inverting circuit 189 must be provided for one of the differential transistors.

Figure 15 is a block diagram of a combining circuit according to a third example of the present invention. The third example utilizes a switching circuit 191 which selects one of the IF electric signals supplied to the input terminals 181 and 182 and having a better S/N value than that of the other signal. To this end, an S/N detector 192 cooperates with the switching circuit 191 for the related selection.

As explained above, the dual balanced optical receiver can attain a stable optical signal reception. In this case, the stability must be maintained over a wide frequency range. Particularly, the stability in terms of the intensity noise should be taken into consideration.

Figure 16 depicts a graph showing intensity noise suppression characteristics. In the graph, the ordinate indicates a relative value in dB of the intensity noise, while the abscissa indicates a frequency of the IF electric signal. The solid line characteristic curve "a" denotes values obtained when a balanced-mixer receiver is not provided, i.e., the receiver shown in Fig. 2, and the broken

line characteristic curve "b" denotes values when the balanced-mixer receiver shown in Fig. 4 is provided. As is apparent, the intensity noise can be greatly suppressed in the latter case, particularly in the frequency range lower than 1 GHz. However, the intensity noise suppression capability is gradually lost in the frequency range higher than 1 GHz. In practice, the frequency of the IF electric signal is determined on the order of several GHz. This means that, in the previously mentioned dual balanced optical signal receiver, there is still room for an improvement of the intensity noise of the local oscillation optical signal  $S_L$ .

Figure 17 is a principal block diagram of an intensity noise suppression arrangement. The arrangement is preferably introduced in each of the optical receivers mentioned previously with reference to Figs. 8, 9, 11 and 12. The concept of suppressing the intensity noise can be understood from Fig. 17. The intensity noise suppressor is characterized by a modulation means 204, a control means 205, and control lines 208 and 209. The modulation means 204 modulates the local signal  $S_L$  with a modulation signal  $S_M$ , and the control means 205 first supervises the related modulation signal component  $S_m$  superposed on the IF output signal produced from the combining means 206 and then minimizes the component  $S_m$  by way of the control line 208 and/or the control line 209.

Other elements cooperating with the intensity noise suppressor (204, 205, 208, 209) are substantially identical to the analogous members explained hereinbefore. That is the photomixing means mixes the received optical signal  $S_r$  with the local oscillation optical signal  $S_L$  and produces two optical signals in two ways, each having an intermediate frequency (IF). The optical signal receiving means 202, 203 receives the respective IF optical signals and transform them into two corresponding electric signals of an intermediate frequency (IF). The combining means 206 produces the IF output signal by subtracting two IF electric signals from each other, and the modulation means 204, as mentioned before, modulates the signal  $S_L$  with the modulation signal  $S_M$ . The control means 205 extracts the modulation signal component  $S_m$  from the IF output signal and controls the optical signal receiving means 202 (or 203) and/or the combining means 206 to ensure that the level of the thus extracted modulation signal component  $S_m$  is minimized, as mentioned before, via the control lines 208 and/or 209.

It is considered that a degradation of the intensity noise suppression is induced by at least one of the following factors; first, an imbalance of the frequency characteristics between the optical signal receiving elements 202 and 203, and second, an imbalance of the amplifiers (not shown but identical

to the amplifiers illustrated, for example, as 121 and 122, in Fig. 8) used in the combining means 206. If the above-mentioned imbalance is not present, the modulation signal component  $S_m$  is cancelled. In practice, the modulation signal component, however, will more or less remain. If, the thus remaining modulation signal component is cancelled, the intensity noise contained in the IF output signal is also cancelled. This cancellation can be achieved by compensating the difference in characteristics between the optical signal receiving means 202 and 203, and/or by compensating the difference in gain or delay time between the aforesaid amplifiers (similar to 121 and 122).

Figure 18 is a schematic block diagram of a first type of an intensity noise suppressor. The modulating means 204 of Fig. 17 is comprised of a usual modulator 214 which receives the modulation signal  $S_m$  given from an oscillator 217. The modulation signal  $S_m$  is also given to a control circuit 215 (corresponding to 205 of Fig. 17). The control circuit 215 is comprised of a lock-in amplifier. The lock-in amplifier carries out a synchronous detection of the modulation signal component  $S_m$  with the signal  $S_M$  having, for example, a sine wave, so that only the modulation signal component  $S_m$  is produced therefrom. The control circuit 215 carries out a gain control, via the line 208, with respect to a photodiode 212 (corresponding to 202 in Fig. 17) to adjust the output level thereof, in accordance with the variation of the  $S_m$ .

A photomixer 211 (corresponding to 201 in Fig. 17) produces two mixed optical signals, one of which is applied to a photodiode 213 (corresponding to 203 in Fig. 17) and the other to the photodiode 212. Then the corresponding IF electric signals, after amplification by amplifiers 218 and 219, are subtracted from each other by a subtractor 220 to produce the IF output signal which contains the modulation signal component  $S_m$ , if present.

Figure 19 is a schematic block diagram of a second type of intensity noise suppressor. Members identical to those of Figs. 17 and 18 are represented by the same reference numerals or symbols, which also applies to later figures. In Fig. 19, the control circuit 215 controls, via the line 209, a phase shifter 231. The phase shifter 231 adjusts the phase difference between the IF electric signals given from the amplifiers 218 and 219 in accordance with the variation of the  $S_m$ . In the figure, a 3 dB photocoupler 221 is illustrated as the photomixing means 201 of Fig. 17.

Figure 20 is a schematic block diagram of a third type of an intensity noise suppressor. The control circuit 215 controls a bias circuit 244 for biasing series connected photodiodes 241 and 242

to adjust the output level of the series connection photodiodes, which provides the function, together with a single amplifier 243, of the subtractor 220 in Fig. 18 or Fig. 19.

Figure 21 is a schematic block diagram of a fourth type of intensity noise suppressor. The control circuit 215 controls an optoelectric device 251. The optoelectric device 251 varies an optical intensity and/or a lightwave phase of the IF optical signal to be applied to the photodiode 241 in accordance with the variation of the component  $S_m$ . The optoelectric device 251 is made of, for example, a Pockels effect device.

Figures 17 through 21 show the intensity noise suppressors effective at frequencies higher than several GHz, each of which is basically joined with a prior art balanced-mixer receiver of Fig. 4. These Figures are intended to facilitate an understanding of the intensity noise suppressor according to the present invention, i.e., the modulator and the control circuit for suppressing the modulation signal component  $S_m$ , that is, the suppression of the intensity noise, and finally, the intensity noise suppressor is joined with a dual balanced optical signal receiver of Fig. 7 according to the present invention.

Figure 22 is a schematic block diagram of a dual balanced optical signal receiver joined with an intensity noise suppressor. It should be understood that although the intensity noise suppressor in Fig. 22 is joined with the dual balanced optical signal receiver according to the first embodiment of Fig. 8, the intensity noise suppressor also can be applied to the embodiments shown in Fig. 9, II, or I2. Further, in Fig. 22, the first type of intensity noise suppressor (Fig. 18) is employed. In this case, two identical control circuits (CNT) 215 and 215' are provided for one polarization side and the other polarization side, but commonly receive the modulation signal  $S_m$  from the oscillator 217. The signal  $S_m$  is also applied to the modulator (MOD) 214. The control circuits 215 and 215' supervise the respective modulation signal components  $S_m$  and  $S'_m$  appearing at the points PNT1 and PNT2 (each corresponding to the output terminal of the subtractor 220 in Fig. 18), respectively, so that the output levels of the optical signal receiving elements II9 and II10 are made equal to the output levels of the elements II7 and II8, respectively.

As mentioned above, in detail, the dual balanced optical signal receiver according to the present invention is advantageous in that the C/N can be improved even when a semiconductor laser and the like with an accompanying high intensity noise is used; a stable coherent lightwave communication can be realized regardless of fluctuations of the polarization, and an increase in the intensity

noise at the higher frequency range can be suppressed even if variances in characteristics of the electric components become large due to, for example, temperature variations or long term use.

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## Claims

1. A dual balanced optical signal receiver, comprising:

an optical mixing/polarization splitting means for producing optical signals having an intermediate frequency (IF) by mixing a received optical signal with a local oscillation optical signal, and then splitting the thus mixed signal into two orthogonally polarized components, or by splitting a received optical signal into two orthogonally polarized components and then mixing each of the thus split orthogonally polarized components with a local oscillation optical signal;

an optical signal receiving means for receiving IF optical signals and transforming said IF optical signals into corresponding electric signals having an intermediate frequency (IF), and;

a combining means for receiving the IF electric signals and combining the two of said IF electric signals having one type of polarization with two other IF electric signals having another type of polarization.

2. A receiver as set forth in claim 1, wherein said receiver is further provided with

a modulation means for modulating a local oscillation optical signal to be input to said optical mixing/polarization splitting means, and

a control means for extracting a modulation signal component from a signal output by said combining means and controlling an input or output of said optical signal receiving means in such a manner that a level of the thus extracted modulation signal component is minimized.

3. A receiver as set forth in claim 1, wherein said optical mixing/polarization splitting means is comprised of a mixing part which mixes a received optical signal with a local oscillation optical signal to produce two mixed optical signals and a polarization splitting part which separates said two mixed optical signals into two orthogonally polarized components and produces a total of four mixed and split optical signals.

4. A receiver as set forth in claim 3, wherein a polarization direction of said local oscillation optical signal is adjusted in such a manner that the two orthogonally polarized components thereof have substantially a same intensity as each other.

5. A receiver as set forth in claim 4, wherein said local oscillation optical signal is supplied to said mixing part by way of a polarization-maintain-

ing fiber, and a polarization plane thereof is rotated relative to a longitudinal axis thereof by an angle of 45°.

6. A receiver as set forth in claim 3, wherein said optical signal receiving means has four optical signal receiving elements which transform the four mixed and split optical signals from said polarization splitting part into corresponding electric signals, respectively.

7. A receiver as set forth in claim 6, wherein said optical signal receiving elements are connected with a subtracting means for receiving outputs from the four optical signal receiving elements and producing two independent IF electric signals by subtracting, on one hand, two IF electric signals having one polarization from each other, and on the other hand, subtracting the other two IF electric signals having the other polarization from each other.

8. A receiver as set forth in claim 7, wherein said combining means further contains a switching circuit which selects from said IF electric signals the IF electric signal having a better S/N ratio.

9. A receiver as set forth in claim 7, wherein said combining means further contains a phase control means for matching phases of two IF electric signals having the same polarization and phases of the other two IF electric signals having the other polarization and a summing means for summing the phase-matched two IF electric signals.

10. A receiver as set forth in claim 9, wherein said combining means further contains a signal intensity control means for equalizing an intensity of each of the two IF electric signals and applying the same to said phase control means.

II. A receiver as set forth in claim I, wherein said optical mixing/polarization splitting means is comprised of a polarization splitting part for receiving said received optical signal and said local oscillation optical signal and separating each of these two optical signals into two orthogonally polarized components and a mixing part which mixes the two polarized components having one polarization and mixes the other two polarized components having the other polarization, which polarized components are given from said polarization splitting part.

12. A receiver as set forth in claim II, wherein a polarization direction of said local oscillation optical signal is adjusted in such a manner that the two orthogonally polarized components thereof have substantially the same intensity.

13. A receiver as set forth in claim 12, wherein said local oscillation optical signal is projected onto said polarization splitting part with a polarization plane rotated relative to the optical axis thereof by an angle of 45°.

14. A receiver as set forth in claim II, wherein said optical signal receiving means has four optical signal receiving elements which transforms the four mixed and split optical signals from said mixing part into corresponding electric signals, respectively.

15. A receiver as set forth in claim 14, wherein said optical signal receiving elements are connected with a subtracting means for receiving outputs from said four optical signal receiving elements and producing two independent IF electric signals by subtracting, on one hand, two IF electric signals having one polarization from each other, and on the other hand, subtracting the other two IF electric signals having the other polarization from each other.

16. A receiver as set forth in claim 15, wherein said combining means further contains a switching circuit which selects from the two IF electric signals the IF electric signal having the better S/N ratio.

17. A receiver as set forth in claim 16, wherein said combining means further contains a phase control means for matching the phases of two IF electric signals having the same polarization and the phases of the other two IF electric signals having the same polarization, and a summing means for summing the phase-matched two IF electric signals.

18. A receiver as set forth in claim 17, wherein said combining means further contains a signal intensity control means for equalizing the intensity of the two IF electric signals and applying the same to said phase control means.

19. A dual balanced optical signal receiver, comprising:

a photomixing means for mixing a received optical signal with a local oscillation optical signal and producing two optical signals each having an intermediate frequency (IF);

an optical signal receiving means for receiving said IF optical signals and transforming said optical signals into two corresponding electric signals having an intermediate frequency (IF);

a combining means for producing an output signal by subtracting each of the two IF electric signals from each other;

a modulation means for modulating said local oscillation optical signal to be input to said photomixing means, and;

a control means for extracting the modulation signal component from the output signal of said combining means and controlling the input or the output of said optical signal receiving means such that the level of the thus extracted modulation signal component is minimized.

20. A receiver as set forth in claim 19, wherein said control means controls the output level of said optical signal receiving means.

21. A receiver as set forth in claim 19, wherein  
said control means controls the phases of each of  
said IF electric signals.

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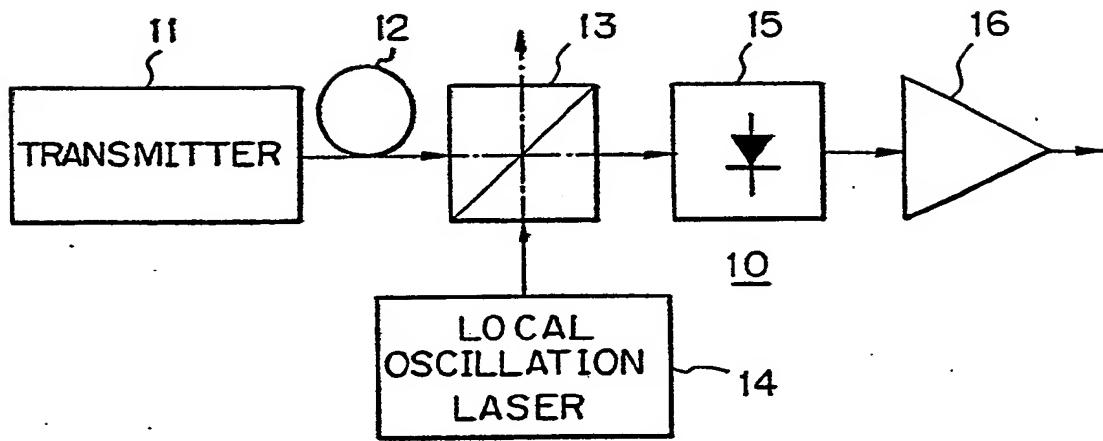
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*Fig. 1* PRIOR ART



*Fig. 3* PRIOR ART

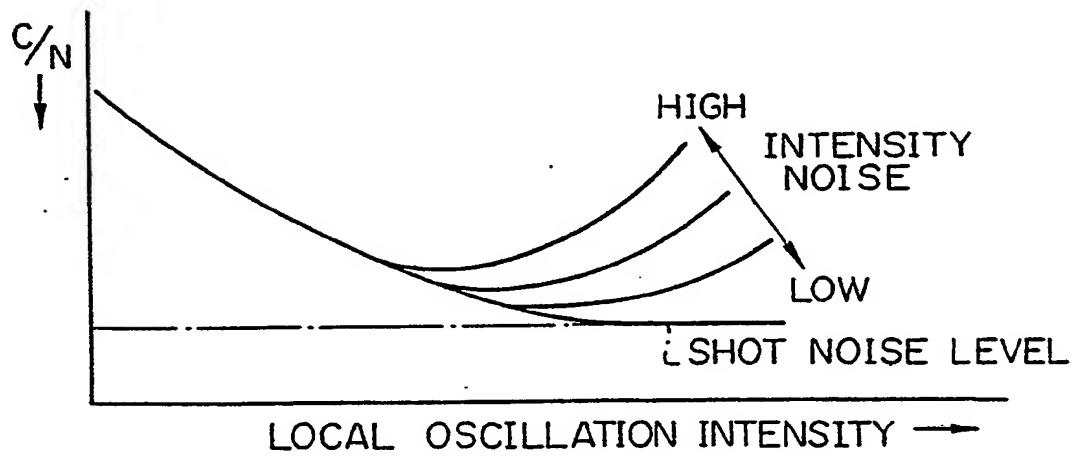
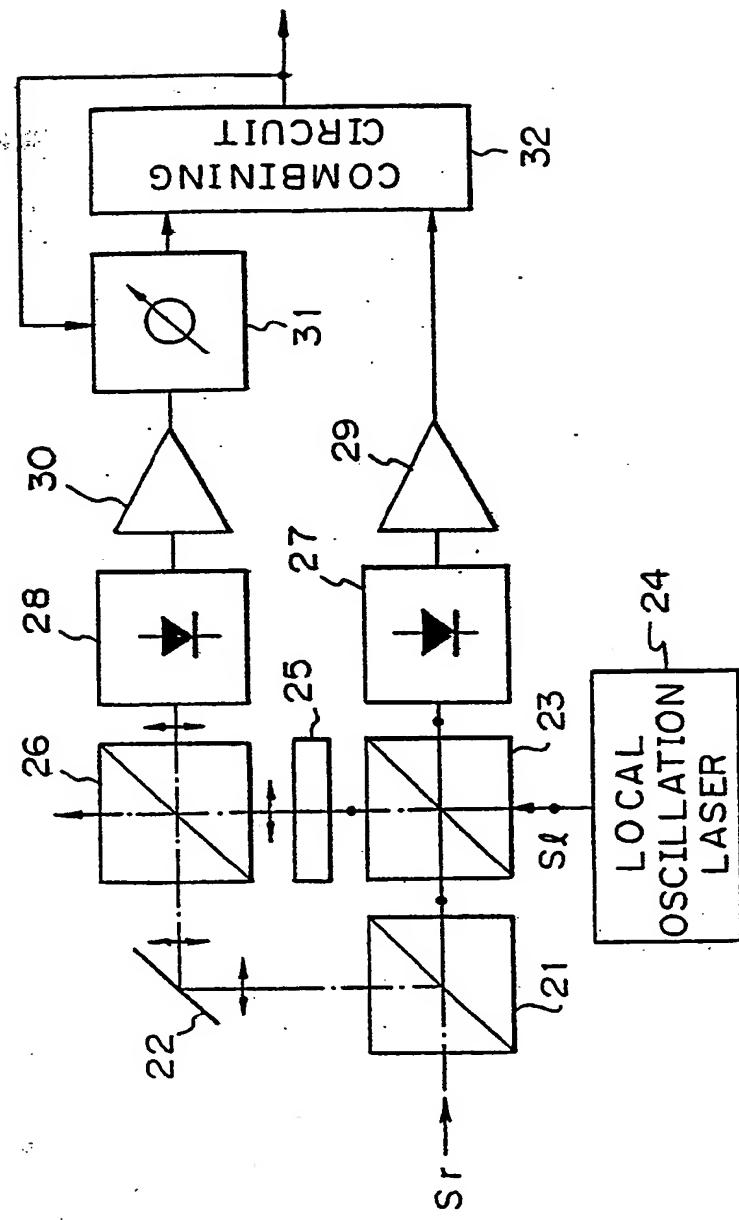
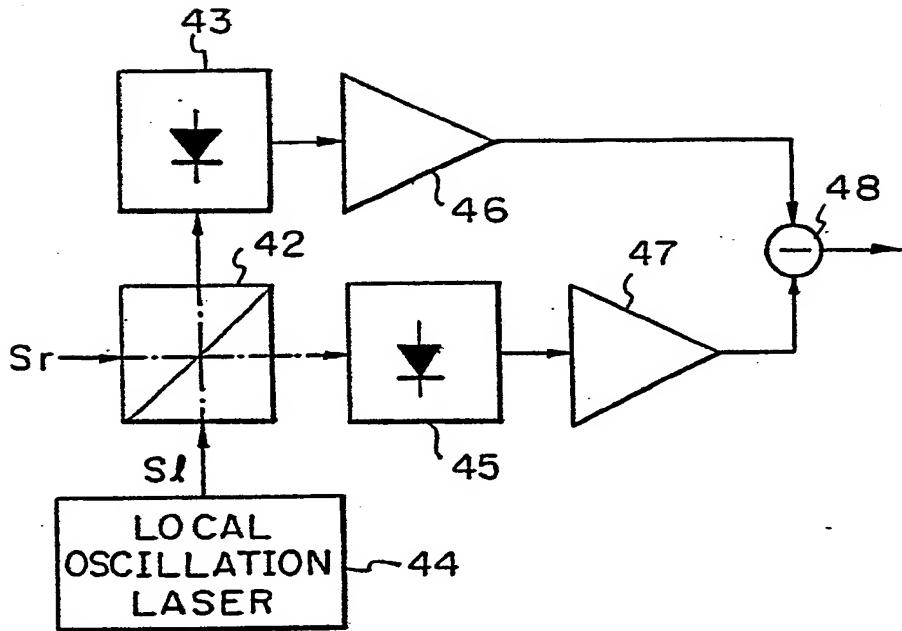
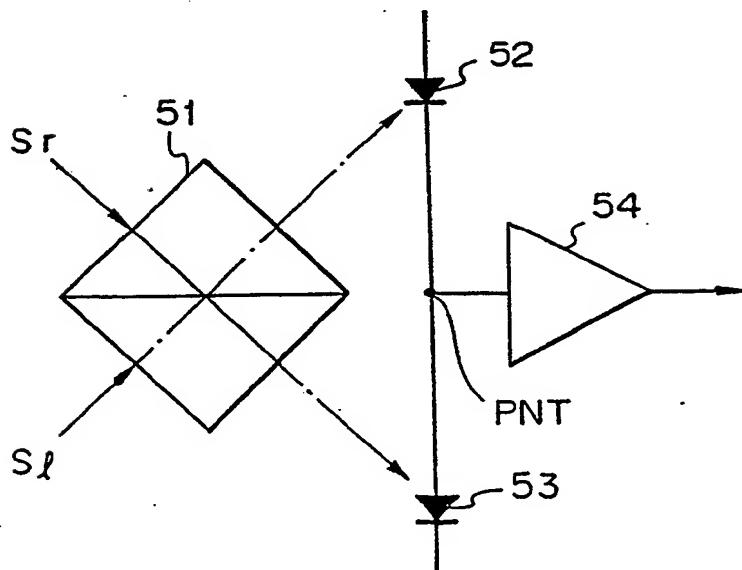
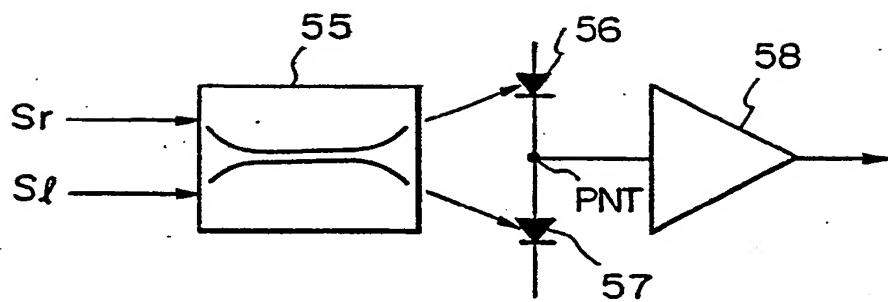


Fig. 2 PRIOR ART

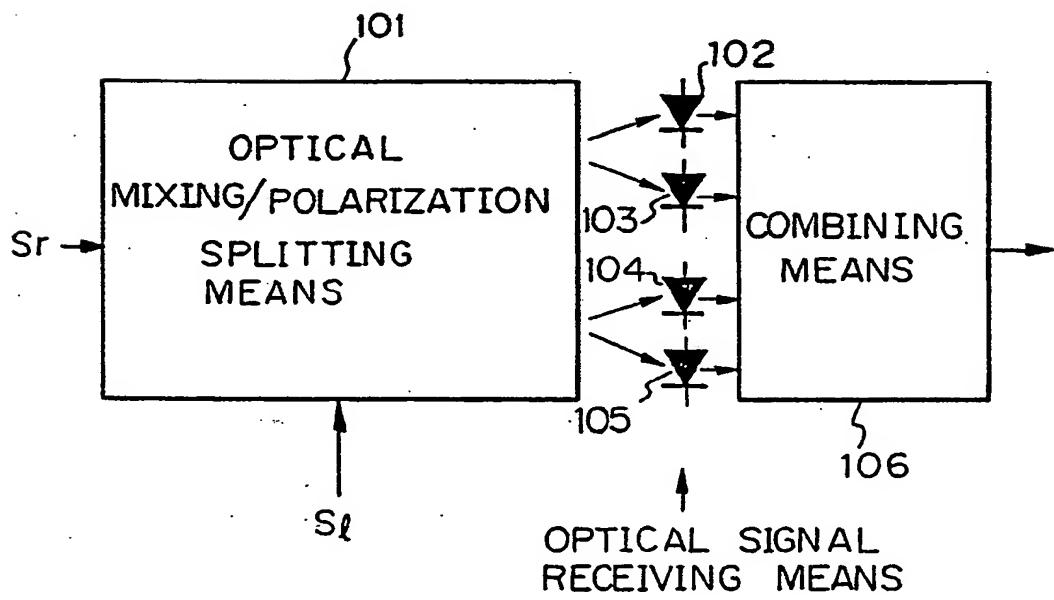


*Fig. 4* PRIOR ART*Fig. 5* PRIOR ART

*Fig. 6* PRIOR ART



*Fig. 7*



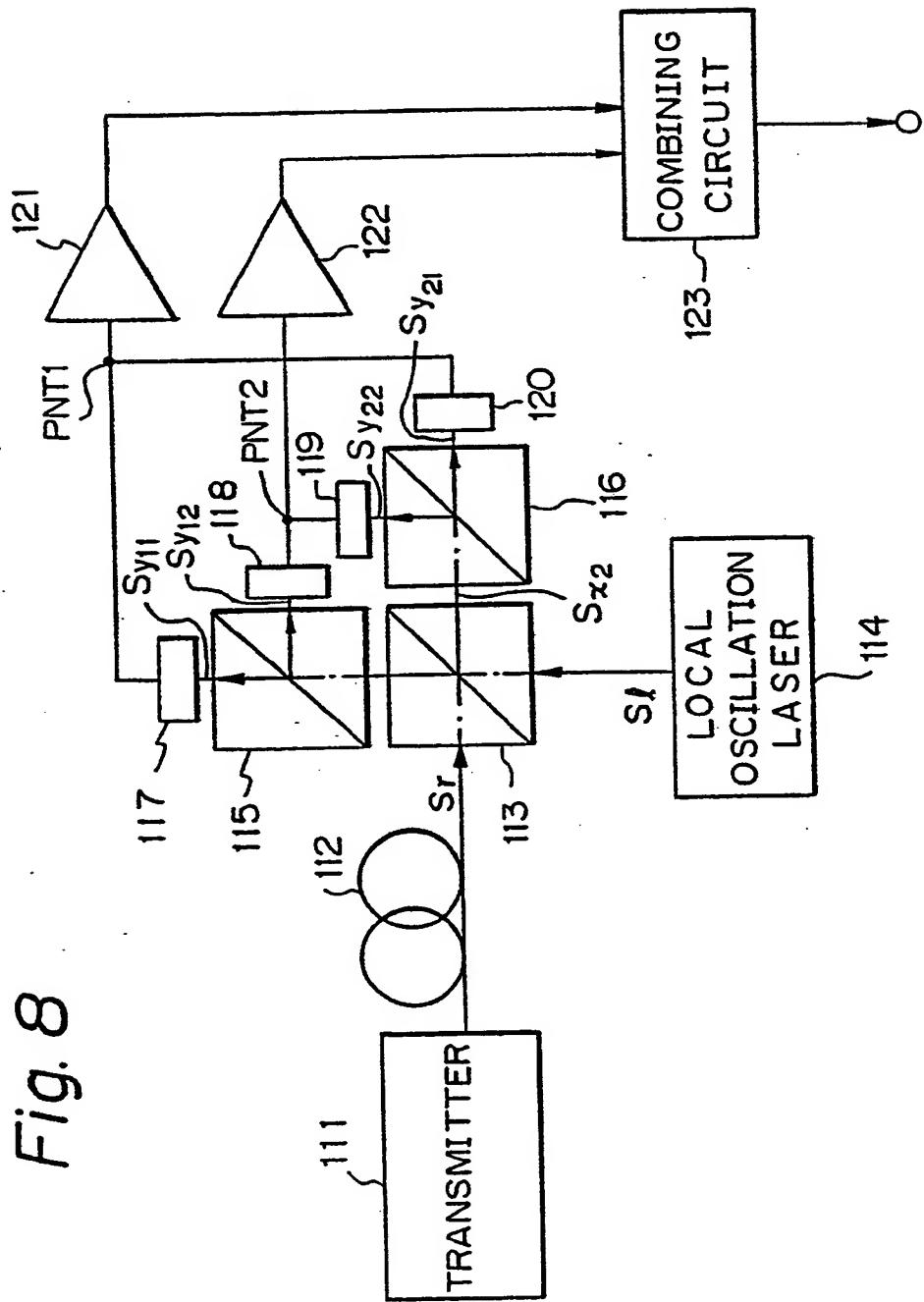


Fig. 9

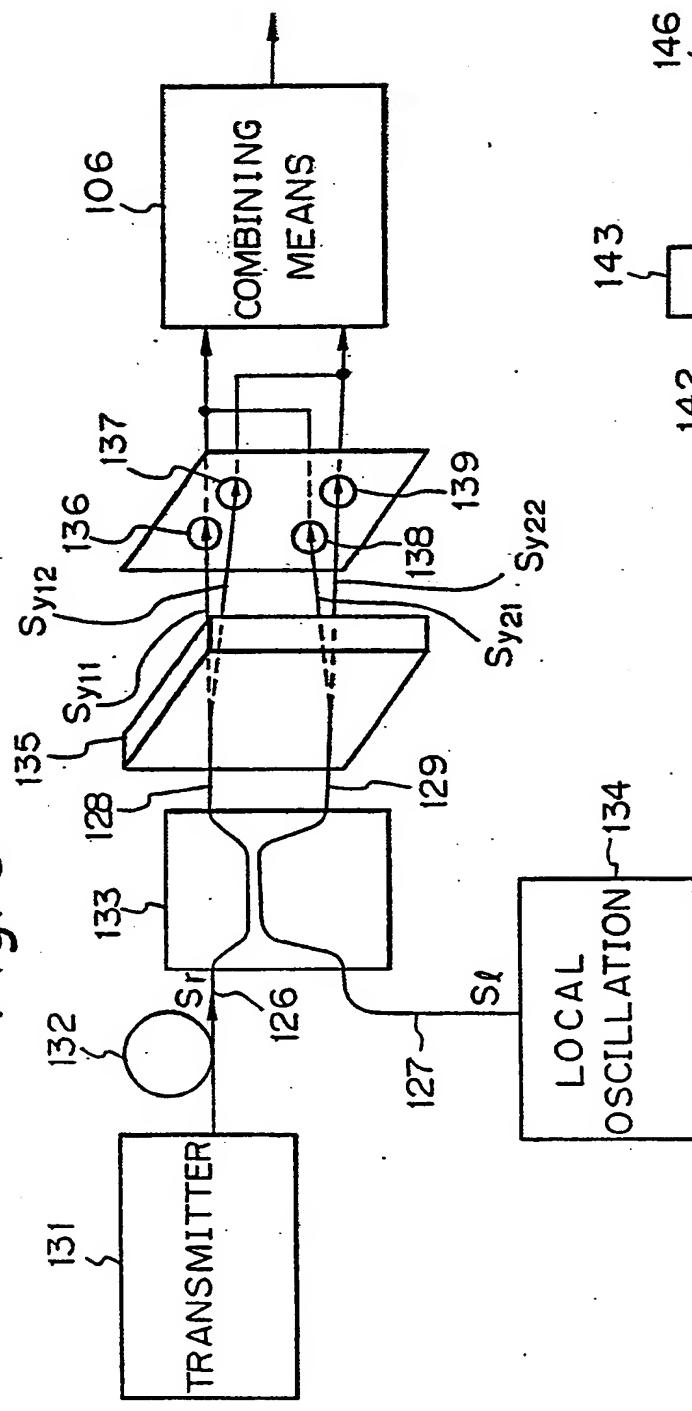


Fig. 10

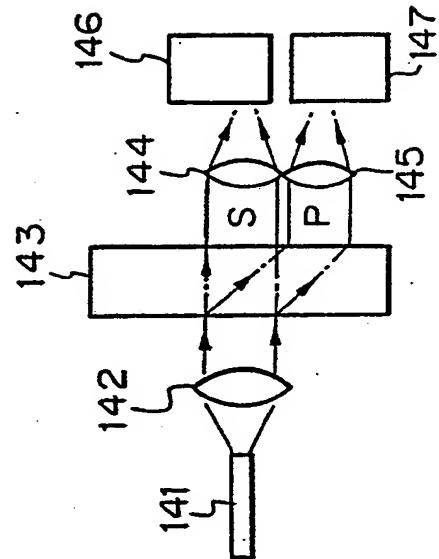


Fig. 11

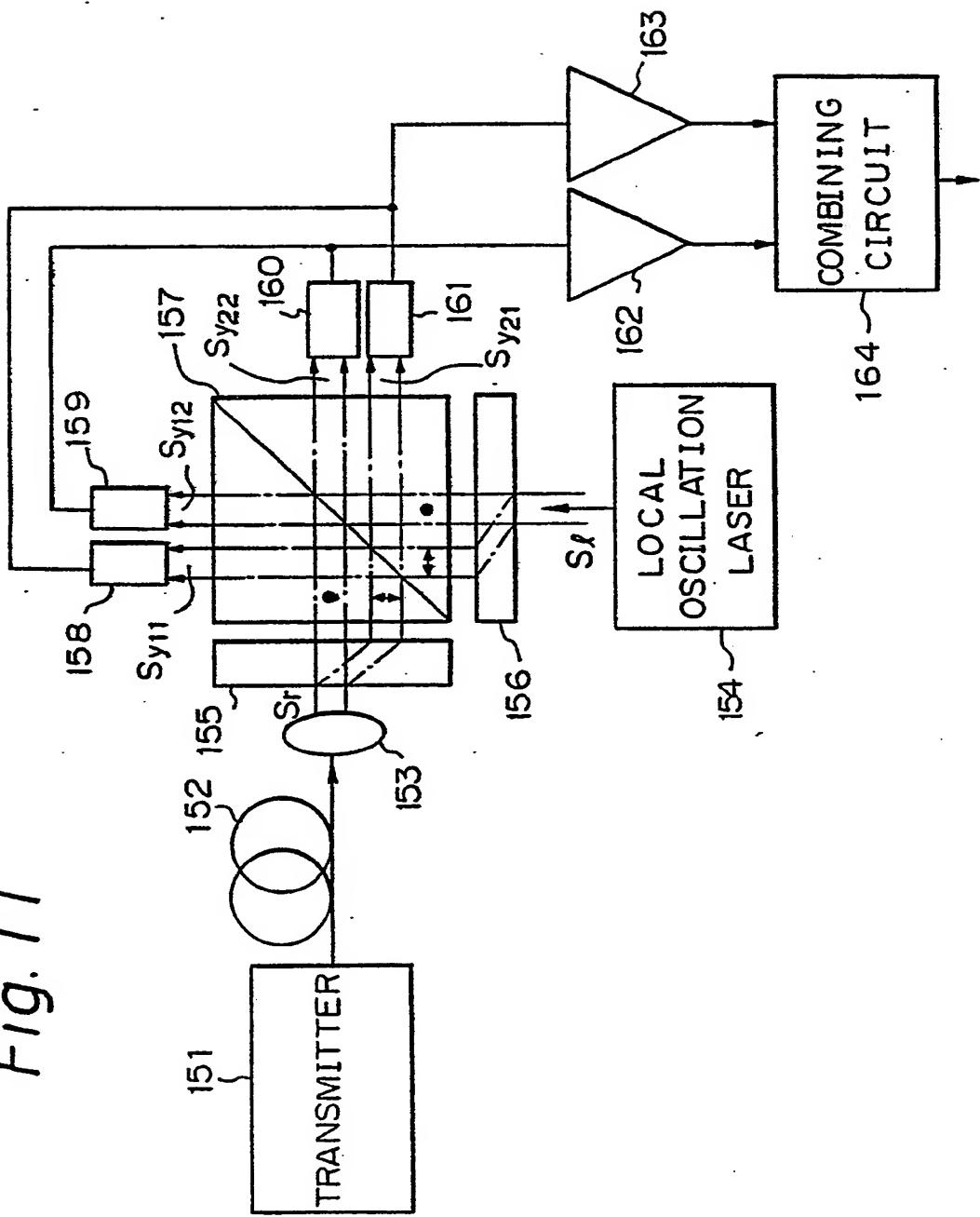


Fig. 12

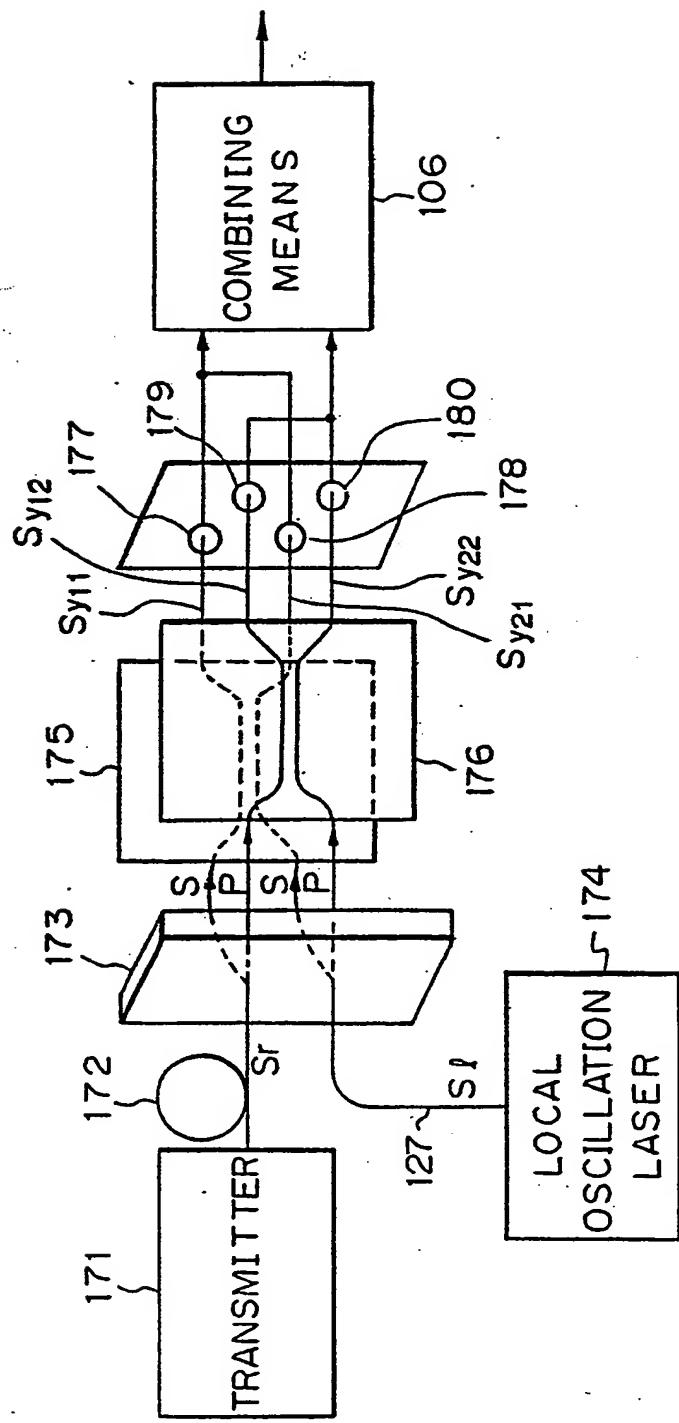


Fig. 13

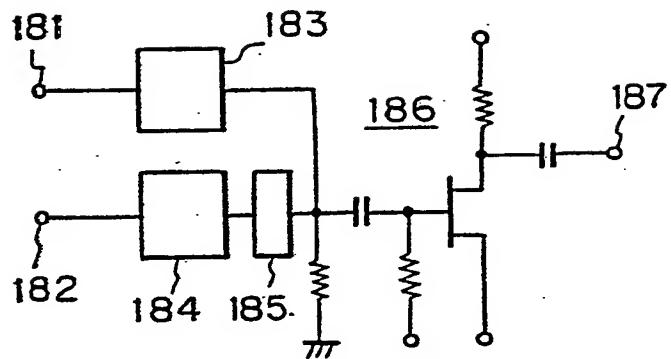


Fig. 14

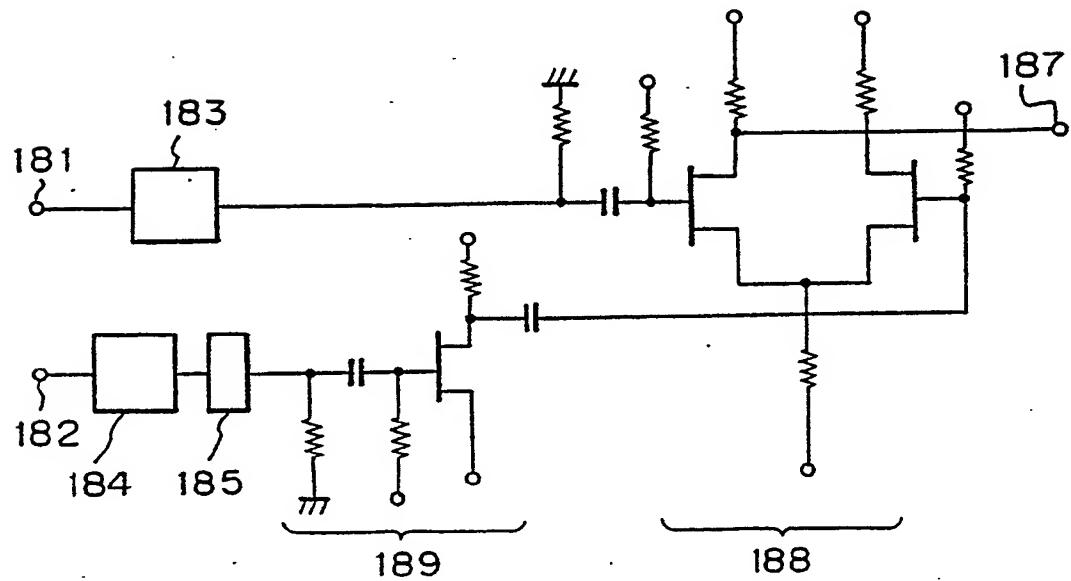


Fig. 15

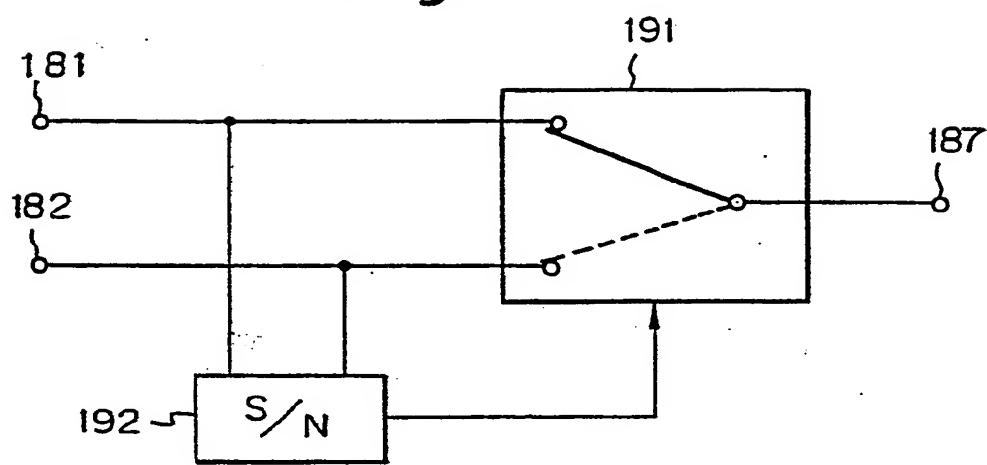


Fig. 16

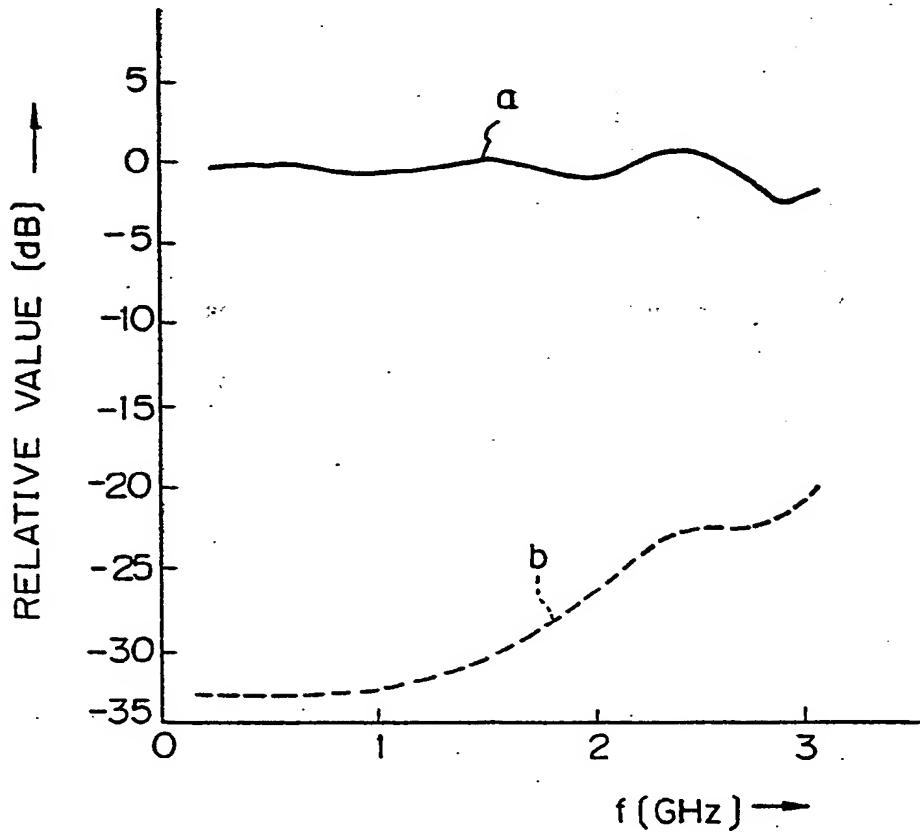


Fig. 17

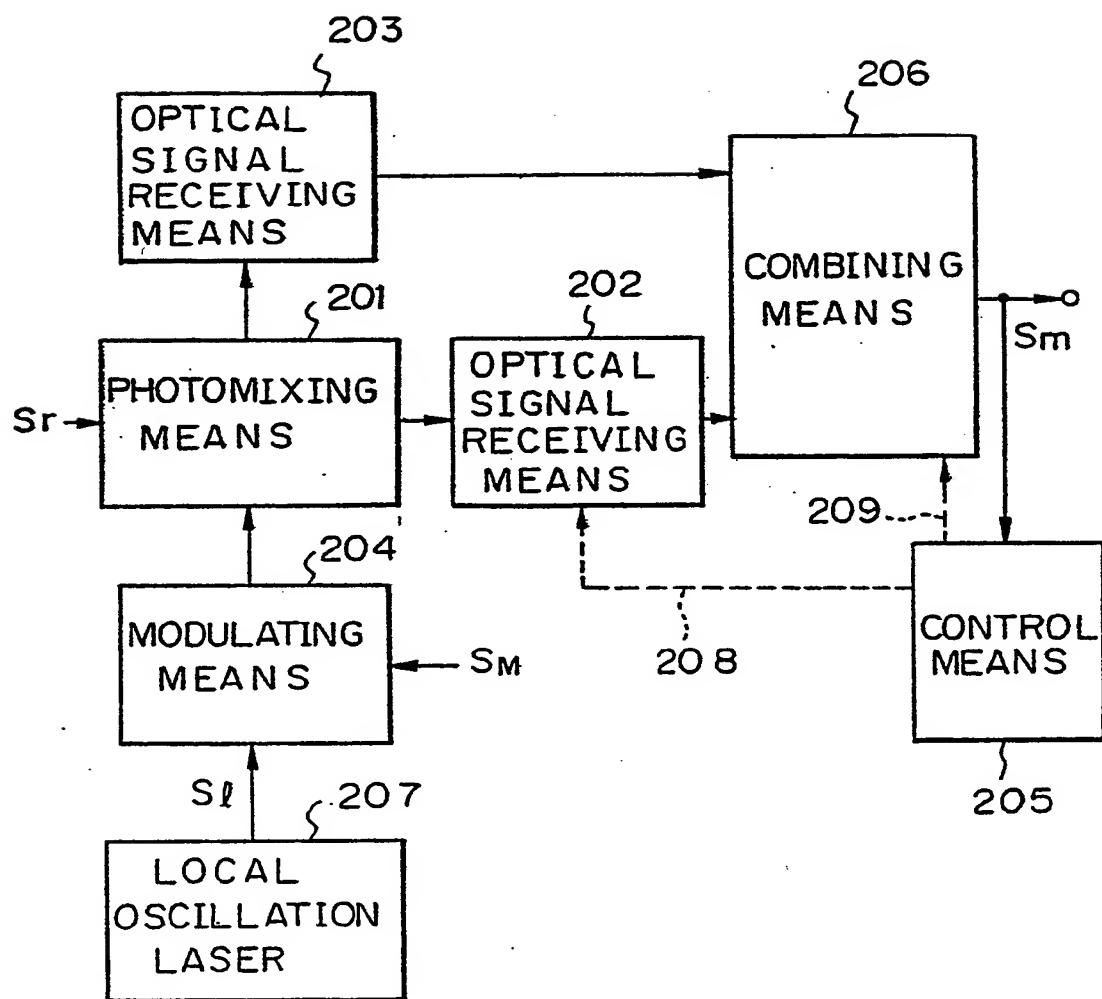


Fig. 18

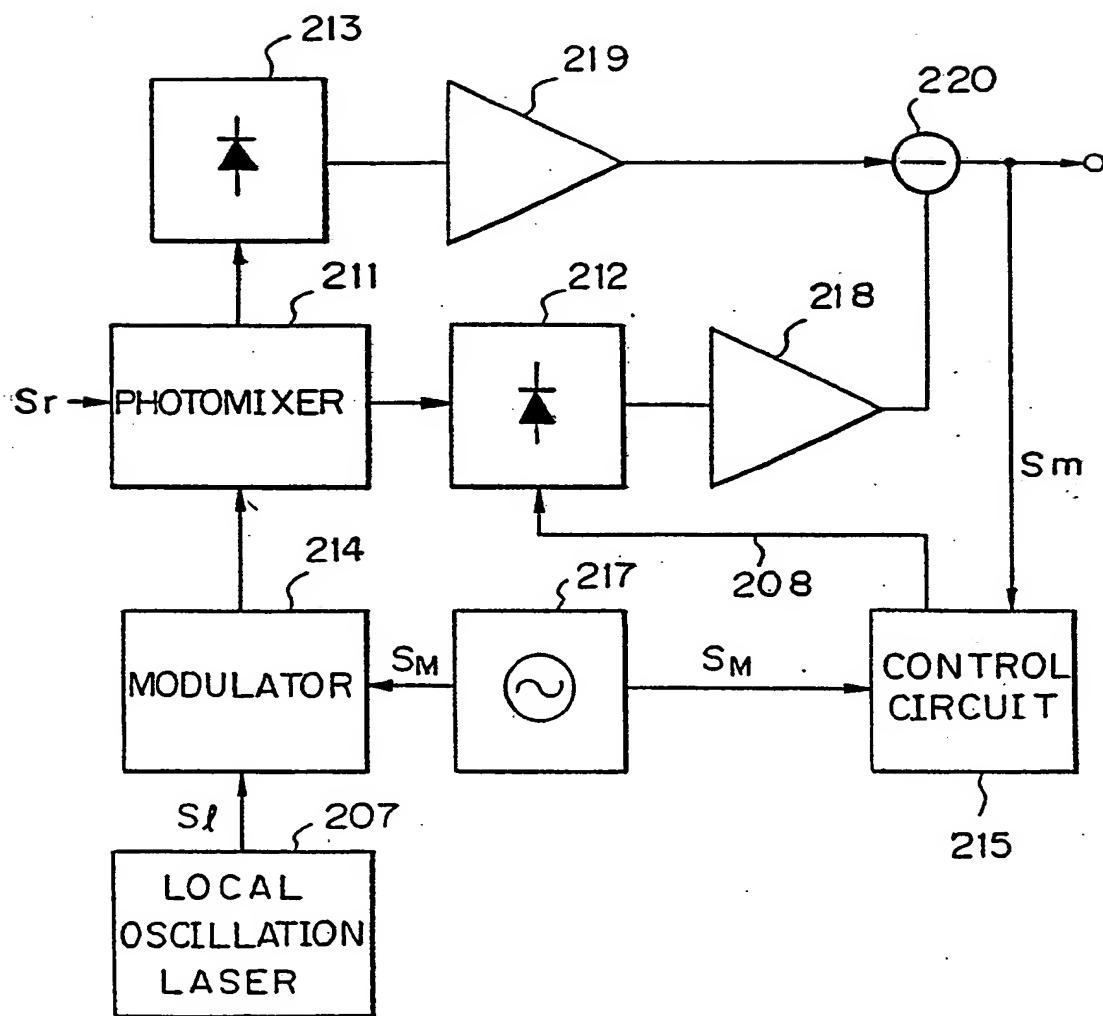


Fig. 19

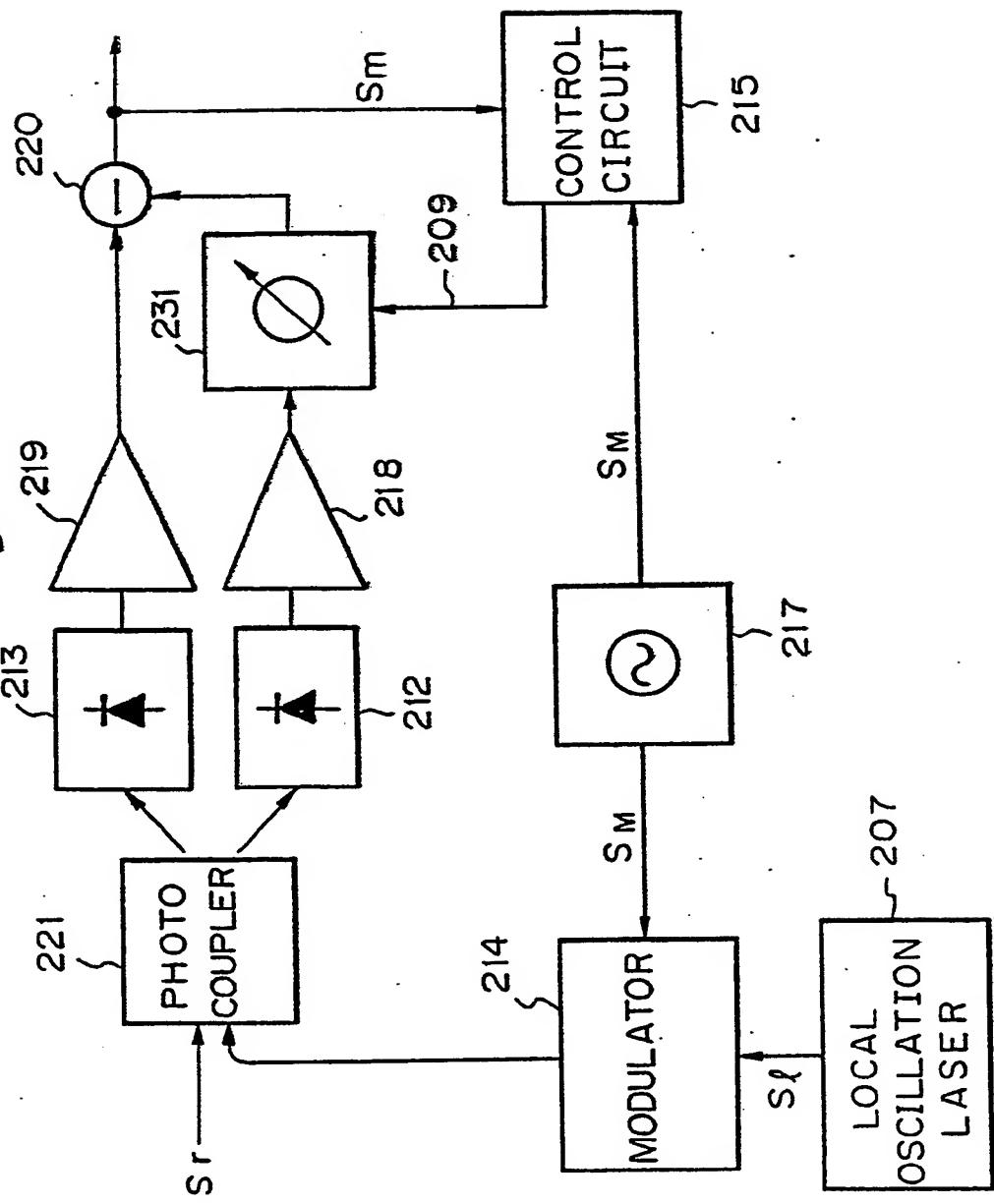


Fig. 20

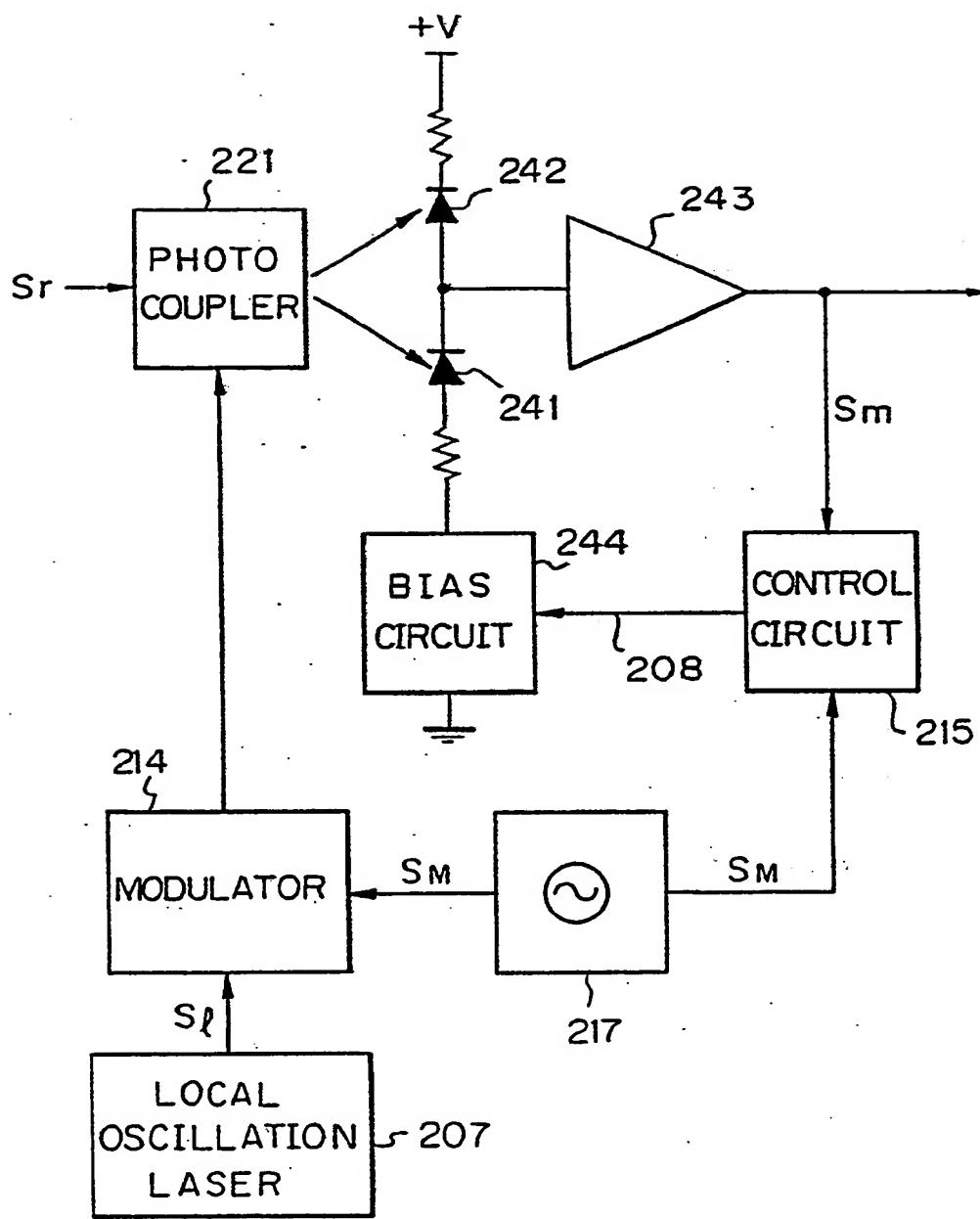


Fig. 21

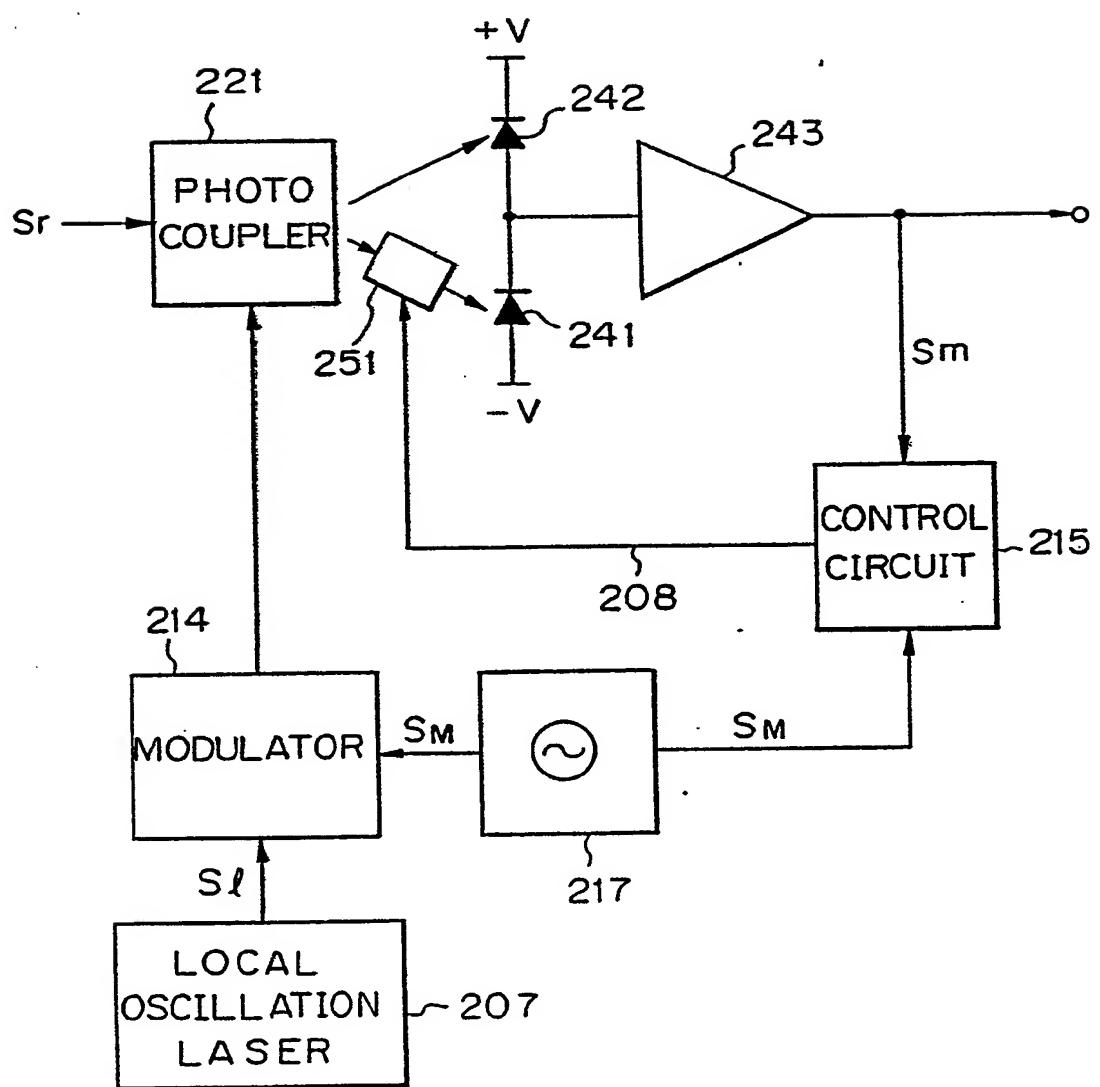
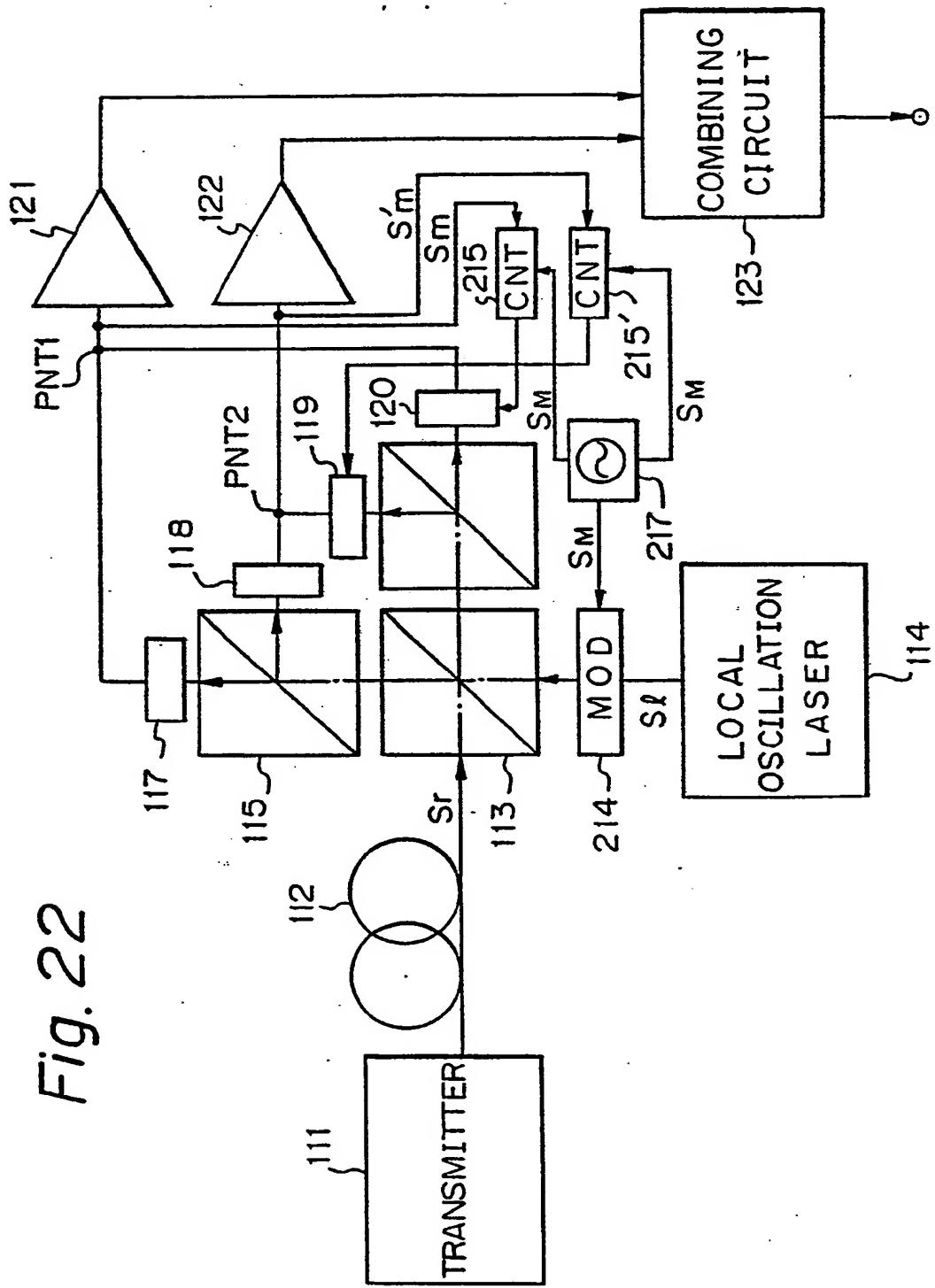


Fig. 22



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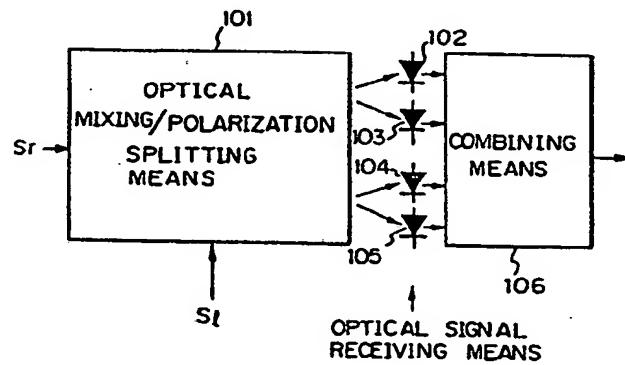
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(54) Dual balanced optical signal receiver.

(57) An optical signal receiver comprising an optical mixing/polarization splitting unit (101) for producing IF optical signals having two orthogonally polarized components, an optical signal receiving unit (102-105) for producing four corresponding IF electric signals, and a combining circuit (106) for combining two IF electric signals having one polarization with the other two IF electric signals having the other polarization, suppressing fluctuation of the polarization and the intensity noise of the related local optical signal. The intensity noise suppression is also effective for IF electric signals having a higher frequency range.

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Fig. 7





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THE HAGUE	25-04-1989	GEISLER J.A.R.	
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